

A HIGH PRESSURE FLOWING OIL SWITCH FOR GIGAWATT, REPETITIVE APPLICATIONS*

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Abstract

A repetitive oil switch for directed energy applications has been developed in a joint effort between teams at the University of Missouri – Columbia, Alpha Omega Power Technologies and the Boeing Company. The switch is operated at test pressures to 17.24 MPa (2500 psi), flow rates to $0.72 \text{ L}\cdot\text{s}^{-1}$ (11.4 gpm), charge voltages to -300 kV and discharge energies to 275 J per pulse at 20 pps. An examination of the electrodes after 250,000 shots with the original design led to the design of an insert device which resulted in higher performance fluid flow within the switch. The flow shaper-enhanced switch was tested for 150,000 shots, the results of which are presented in the following paper. Electrode lifetime has been evaluated for stainless steel under the original and enhanced fluid flow conditions and is reported.

I. INTRODUCTION

Early studies at moderate pressures have shown breakdown strength in liquids to be a function of pressure up to at least 350 psi [1]. More recent studies have shown significant improvement in the breakdown jitter of liquid switches when the liquid was pressurized and flowed [2]. Single-shot work on high pressure liquid switches at the

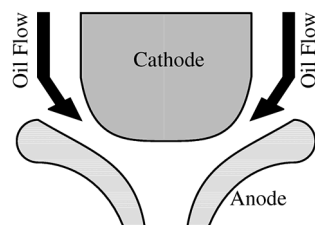


Figure 1. Cutaway diagram of the switch geometry

Table 1. Parametric description of the UMC test stand.

Charge Voltage	-300 kV
Pulse Current	28.75 kA
PFL Impedance	4.8 Ω
Pulse Risetime	16 ns
Pulse Length	70 ns
Repetition Rate	20 pps

University of Missouri – Columbia (UMC) and Alpha Omega Power Technologies has provided additional evidence to support the effects of pressure upon breakdown voltage [3, 4].

The project goal is to develop high pressure oil switching technology that results in low switching jitter and long electrode lifetime. Typical operating parameters are presented in Table 1. A cross section of the switch geometry is shown in Figure 1. As illustrated in the drawing oil, flows around the cathode electrode and into a contoured anode throat section. The switch gap spacing is a function of the operating pressure and increases with pressure. Gap spacing is set to 1.02 mm while the switch is under atmospheric pressure with an estimated error of less than $\pm 15 \mu\text{m}$.

II. UMC TEST STAND

A. Pulse Generator

The pulse generator used for testing the high pressure switch concept under repetitive pulse conditions is a 4.8 Ω , 70 ns water pulse forming line (PFL). The water PFL is pulse charged to a maximum of -300 kV in 2.5 μs

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through a pulse transformer. A capacitor-based pulse modulator is used to pulse charge the PFL. The modulator consists of a hydrogen thyatron, a capacitor bank, and a snubber network as shown in Figure 2. The capacitor bank is charged up to 26 kV, storing 273 J. Twelve 50 Ω cables 15.25 m in length are used to provide 70 ns of time-isolation between the PFL and the load resistor.

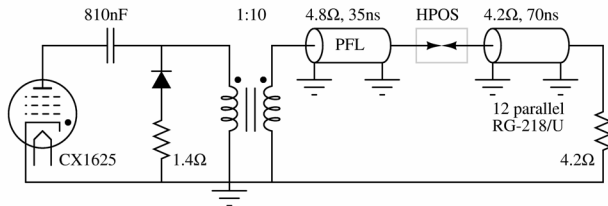


Figure 2. Basic circuit diagram showing pulse modulator to the left of the transformer and the water PFL to the right of the transformer.

The charge and discharge voltages are monitored with a pair of D-dot probes. The probes are installed in the outer wall of the cylindrical metal structure that surrounds the switch. A liquid tight fit is made via Swagelok fittings and the output is fed into a passive integrator. A typical output voltage waveform is presented in Figure 3 which shows a 10-90 rise time of about 16 ns.

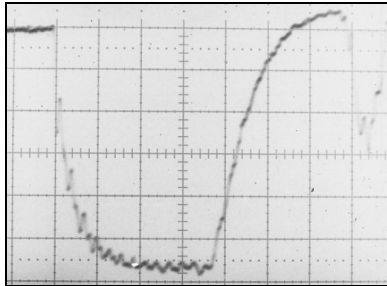


Figure 3. Typical discharge waveform recorded at the anode. 11.4 kV/div vertical resolution, 20 ns/div horizontal resolution.

B. Hydraulic Power Supply

Hydraulic power was provided by a portable hydraulic pumping unit. The pump generated flow rates up to 0.72 L·s⁻¹ at pressures in excess of 17.24 MPa. The pump had an adjustable stroke compensation which was used to adjust volumetric flow at various pressures. The oil used for test purposes was an electrically insulating, thermally conductive, synthetic olefin-based liquid (PAO).

Fluid diagnostics used on the test stand included a pair of analog pressure gages and various flow rate sensors. Pressure in and across the switch was monitored with a pair of ENFM bourdon-tube pressure gages that had pressure resolution to 10 psig. Both the inlet pressure and the outlet pressure were recorded, however only the inlet pressure is used for reporting data in this paper. Overall volumetric flow rate was monitored in the oil return line

with a viscosity compensated turbine sensor manufactured by Cox Instruments. A pair of Hedland variable area flow sensors monitored relative flow rates in the two oil lines that fed the high pressure switch.

High performance filters were installed to increase the cleanliness of the oil both entering and leaving the switch. The filter elements are rated to retain more than 99.9% of particles 0.45 μ m or larger that are suspended in the oil passed through the media.

III. TEST RESULTS

The high pressure switch was tested under both single shot and repetitive conditions over a range of pressures, flow rates and temperatures. The primary experimental effort focused on improving jitter and electrode lifetime, pursuant to the stated goals of the project. The single shot work presented takes a look at the statistical nature of breakdown voltage, electric field strength, and jitter under typical test conditions.

The high pressure switch geometry is a pin in hole type geometry as indicated in Figure 1. In the original geometry oil is forced to flow around the cathode and down through the center of the anode. Based on a computational fluid dynamics simulation a flow shaping element was proposed that reduced the cross sectional area of the oil path, thereby effectively eliminating eddy flows near the stressed region of the switch. The gap spacing was generally set at 1.016 mm and the electrodes had a pressure dependent field enhancement factor of about 11.7 at 13.79 MPa and 11.0 at 17.24 MPa. The peak field stress expected at 250 kV and 13.79 MPa was approximately 2.3 MV·cm⁻¹. Pressure drop across the switch varied, depending on the flow rate, from 69 kPa (10 psi) at the lowest flow rates to 207 kPa (30 psi) at the highest flow rates.

C. Single Shot Tests

An analysis of the single shot switch performance was undertaken to define a hold-off strength for oil under test conditions. Tests were performed at six pressures and two volumetric flow rates. At each combination of pressure and flow a sample of 50 shots were recorded, each shot separated in time by greater than 45 seconds. The tests were performed using 304 stainless steel electrodes following 140,000 shots of electrode break in and conditioning. The D-dot probe adjacent to the charge electrode was used to record the waveforms. Post-processing was performed to reconstruct the actual charge waveform and generate an electric field strength value.

Plots of the electric field strength at breakdown as a function of pressure for two volumetric flow rates are shown in Figures 4 and 5. The graphs show a solid line representing the linear least-squares fit to the data. The dashed line represents the boundaries of a 90% confidence interval of the data at each pressure. The small

slope of the solid lines combined with the relative width of the confidence intervals suggest that the electric field strength at breakdown is not *strongly* affected by pressure over the range of pressures reported.

Breakdown jitter was noted earlier to be an important performance parameter for the high pressure switch. The data plotted in Figure 4 shows no *strong* correlation between jitter over the range of pressures reported. The 1σ jitter for the data reported is $\pm 9.7\%$ at 13.79 MPa and $\pm 10.0\%$ at 17.24 MPa. Examination of the 90% confidence interval data in Figure 5 does show some correlation between breakdown jitter and pressure, with jitter decreasing as a function of pressure. The 1σ jitter is $\pm 11.4\%$ at 13.79 MPa and $\pm 8.1\%$ at 17.24 MPa. These results indicate a reduction of around $\pm 3.3\%$ over the range of pressures examined.

D. Repetition Rate Tests

The switch was tested under repetitive conditions for several hundred thousand shots. The repetition rate tests were conducted to establish the relationship between oil pressure, volumetric flow rate, breakdown hold-off jitter and recovery, and electrode wear. Waveforms were photographed to obtain information about total jitter and mean breakdown electric field strength under various rep rates.

Figure 6 shows the results of operation at 1 pps and at constant pressure, constant flow rate and constant oil temperature. The time jitter in the figure, measured from the leading edge of the pulse train to the trailing edge of the pulse train, is approximately 125 ns or 5 % of the time to peak. Qualitative analysis of the repetition rate data

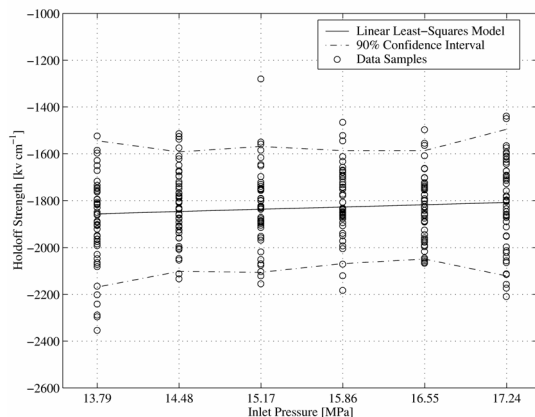


Figure 4. Electric field strength at breakdown versus switch inlet pressure. Net volumetric flow rate of $0.379 \text{ L}\cdot\text{s}^{-1}$ (6 gpm).

over 1000 shot bursts indicates that jitter is within the same order of magnitude as the single shot jitter. The switch has been tested at up to 22 pps and the results are nearly identical to single shot and 1 pps results.

Electrode lifetime tests were conducted under rep rate conditions. Oil pressure was generally kept around 13.79

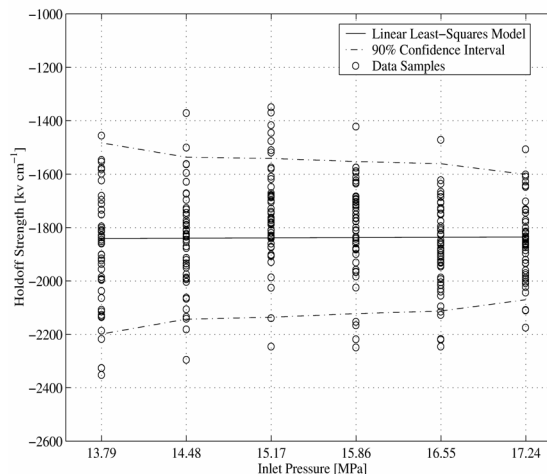


Figure 5. Electric field strength as a function of switch inlet pressure. Net volumetric flow rate of $0.568 \text{ L}\cdot\text{s}^{-1}$ (9 gpm).

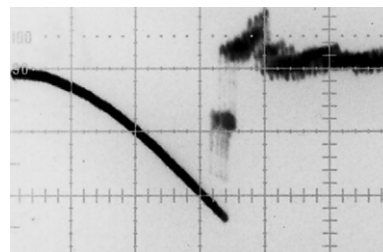


Figure 6. Five shot bursts at 1 pps. 71.4 kV/div vertical resolution, 500 ns/div horizontal resolution.

MPa (2000 psig), flow rates varied from $0.379 \text{ L}\cdot\text{s}^{-1}$ to $0.681 \text{ L}\cdot\text{s}^{-1}$ and temperatures were kept between 18°C and 32°C . Tests were performed at repetition rates between 1 pps and 20 pps, with the majority of the tests taking place at 15 pps and in 1000 shot bursts.

Repetition rate testing was performed with two distinctly different fluid path designs. The original switch concept had a geometry that resembles that shown in Figure 1. In the interest of improved switching performance a second design was implemented to modify the oil path. The design was meant to reduce random swirling that was predicted by a computational fluid dynamics simulation of the original geometry. The flow shaper featured a constrained oil path with less cross sectional area to increase the average oil velocity and vanes in the fluid path to establish a swirl-free velocity profile within the electrically stressed regions of the switch.

The original switch design was run with 304 stainless steel electrodes. More than 250,000 shots were taken in the course of this first test series. When the switch was removed from the test stand the discharge pattern was recorded. The discharge is supposed to occur within a band on the side of the pin electrode. The arc sites were uniformly distributed over a band that was approximately

1.7 cm wide. A photograph of the discharge band is shown in Figure 7.

A set of K-33 sintered copper-tungsten electrodes were fabricated and installed in the hopes of increased performance over the stainless steel electrodes. In addition to the electrode material change the flow shaper was installed. After less than 4000 shots under rep rate conditions rapid increases in the system pressure were observed during operation. The switch was removed and the electrodes were inspected. The wear pattern was noted to be very localized, showing signs consistent with spallation. The pressure variations observed during operation were apparently a result of pieces of the electrode getting caught in a down-stream needle valve. A photograph of the damage is shown in Figure 8.

A second set of 304 stainless steel electrodes were installed with the flow shaper and lifetime tests were restarted. After approximately 140,000 shots the single shot tests already reported were performed. Following the single shot tests the electrodes were removed. The wear pattern that had developed was more distinct and defined than that seen on the first 304 stainless steel electrodes. The width of the discharge band had decreased by 41 % to about 1.0 cm. A photograph of the wear pattern is shown in Figure 9.



Figure 7. Type 304 stainless steel electrode following 250,000 shots with original oil flow configuration. Width of the arc band ~ 1.7 cm.

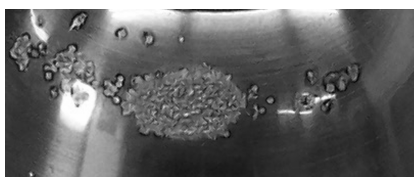


Figure 8. Elektro-Metall (formerly Schwarzkopf) K-33 electrode following 4000 shots with enhanced oil flow configuration. Width of main spot (top to bottom) ~ 0.7 cm.



Figure 9. Second type 304 stainless steel electrode after 150,000 shots with enhanced oil flow configuration. Width of the arc band ~ 1.0 cm

Throughout all of the tests described in this paper the dielectric oil was not flushed and replenished. Chemical analyses were performed on the oil and several interesting findings have resulted. Water content was expected to be around 200 to 300 ppm since the oil reservoir is open to the atmosphere and tests were performed in a region notorious for high humidity. Despite expectations, the tests revealed that water content was around 13 ppm.

As noted in previous works significant quantities of carbon are generated during discharge under high pressure [4]. Following the first 250,000 shots the oil return line filter was examined and found to be jet black from all of the carbon deposits. Based on this examination the filter was changed between the first 304 stainless steel electrode tests and the K-33 electrode tests.

IV. CONCLUSIONS

The high pressure oil switch test stand at the University of Missouri – Columbia has been described. The system uses a pressurized flowing dielectric as a switching medium for a repetition rate pulse generator. Recent tests of the system under rep-rate conditions for 250,000 shots indicate that electrode lifetime may be greater than 10^7 shots. Tests are planned to validate the switching jitter under repetitive conditions.

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